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TECH. NOTE
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ROYAL AIRCRAFT ESTABLISHMENT

F A R N B O R O U G H, H A N T S

TECHNICAL NOTE No: INSTN.135

A VARIABLE INDUCTANCE ACCELERATION TRANSDUCER

by

H.K.P.NEUBERT, Dr.-Ing.

UNCLASSIFIED

U.D.C. No. 53.082.74 : 621.3.083.7

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A variable inductance acceleration transducer

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H.K.P. Neubert, Dr.-Ing.

R.A.E. Ref: Instn: 006/10

SUMMARY

The note describes a general purpose variable inductance acceleration transducer for ranges of ± 3g and ± 9g. It may be adapted with minor modifications for ranges up to about ± 100g. It has been designed for use with the carrier bridge amplifiers Types IT.1-5-51 and IT.1-6-51 operating at a carrier frequency of 2,000 c/sec. The cut-off frequencies of the transducer are 70 c/sec for the ± 3g and 100 c/sec for the ± 9g range. Deviation from linearity of calibration is less than 3% of full scale and the effect of transverse acceleration is approximately 1.5% for full range acceleration applied in a transverse direction. The zero shift at elevated temperatures is about + 0.04% per °C and the change in sensitivity about - 0.1% per °C. At an initial inductance level of 70 mH in each coil the average full scale variation in inductance is ± 15%.

Design parameters for the bridge resistance values are derived and plotted for two independent conditions:- (a) freedom from resistive noise and (b) maximum useful power output from the bridge. The effect of cable capacitance and of mutual coupling between the transducer coils are also discussed.

LIST OF CONTENTS

LIST OF ILLUSTRATIONS

1 Introduction

The acceleration transducer Type IT.1-22F-31 has been designed as a general purpose transducer for the measurement of vibration and the resonance testing of aircraft on the ground and in flight. The two ranges of ± 3g and ± 9g, with cut-off frequencies at 70 c/sec and 100 c/sec respectively, will cover the most common magnitudes of vibration amplitudes and frequencies in these applications. It is designed for use with a carrier bridge amplifier and galvanometer recorder, providing a frequency range of zero to about 100 c/sec. The transducer contains two push-pull variable inductances which are connected to form two adjacent arms in the bridge circuit of the amplifier. The carrier bridge amplifier Type IT.1-5 and IT.1-6-51 contain two electrical integrating stages, so that when used with these amplifiers the transducer may be used for the measurement of vibration amplitudes.

2 Description

The construction of the transducer is shown in Fig 1. Fig 2a shows a photograph of the complete instrument and Fig 2b an exploded transducer. It consists essentially of an armature sub-assembly situated and appropriately spaced between two identical coil sub-assemblies. The armature and coil sub-assemblies are housed in a rigid body. The armature sub-assembly consists of a bar-shaped ferro-magnetic armature suspended by two leaf springs which are soldered to the armature and a supporting ring. A coil sub-assembly comprises an E-shaped ferro-magnetic core with a coil of 1,200 turns of Lewmex wire of 46 S.W.G. The ferro-magnetic material is either ferro-nickel laminations or Ferroxcube III. Core and coil are moulded into a dural cup with a polyester resin (Marco Resin), which polymerises at room temperature. The free surfaces of the legs of the core are flush with the top of the cup and the resin. The initial air gap between armature and E-core on both sides of the armature may then be adjusted to the required value by means of copper shims of appropriate thickness.

If acceleration is applied in the working direction of the transducer, i.e. in the direction of the long axis of the transducer housing, the armature will deflect, thus changing the airgaps in the magnetic circuits of the coils in a push-pull manner, and a push-pull variation of inductance in the two coils will result. The terminals of the two coils are connected to a three cored cable which is cleated to the housing.

The transducer housing is filled with damping oil of the appropriate viscosity and sealed with rubber washers and a ring nut. At one end of the housing an oil expansion chamber is provided to avoid oil leakages at elevated ambient temperatures.

The overall size of the transducer is 1.9 × 1.42 × 1.13 inches; its weight (without cable) is 3 ounces. The detachable base has two fixing holes for 4 BA screws separated by 1.16 inches.

3 Mechanical characteristics

3.1 Range and linearity

The standard ranges being manufactured at present are ± 3g and ± 9g. Other ranges may be made by using springs of a different thickness or material. It is expected that in this way ranges from ± 3g to about ± 100g may be obtained.

Within its range the calibration curve is linear within 3% of full scale. Fig 3 shows a typical calibration curve for a transducer of range ± 9g. The scatter in the slopes of the calibration curves (i.e. in sensitivity) of a batch of transducers is not greater than 10%.

If the acceleration transducer is used to measure displacement (vibration amplitude) care has to be taken not to exceed the range of the transducer, as outside the range the non-linearity rapidly increases. Care has also to be taken to ensure that a reasonable fraction of the range is being used, as, in common with all other instruments, the transducer cannot be expected to give the same absolute accuracy for a small fraction of its range as for its full range. Taking the usable range of the transducer as from 0.1 times full range to full range, the upper and lower limits of amplitude at various frequencies are as given in Fig 4. For example, at 10 c/sec the ± 3g transducer may be used in the amplitude range 0.03 to 0.3 inches, and the ± 9g transducer in the amplitude range 0.1 to 1 inch.

3.2 Frequency response

With a filling of silicone damping oil of viscosity 20 centistokes the damping ratio of the ± 9g acceleration transducer is approximately 60% of critical damping at room temperature. Fig 5 shows typical frequency response curves of transducers for ± 9g and ± 3g ranges with damping adjusted to this value. However it should be born in mind that, although the viscosity of silicone oil is relatively independent of temperature, in extreme cases the variation of viscosity with temperature may be appreciable. Fig 6 shows the damping ratios of the transducer, computed from the viscosity -temperature characteristics of the oil, the nominal damping ratio of 0.6 being adjusted at + 25°C. Near room temperature the variation is approximately - 2.2% of the nominal damping ratio per °C.

3.3 Transverse sensitivity

If acceleration is applied in a direction perpendicular to the working axis of the transducer, an error signal will result. To investigate the magnitude of this effect three transducers of ± 9g range have been subjected to transverse accelerations of plus and minus 9g to produce compression or tension and edgewise shear in their armature springs. The results (in terms of percentage of full scale) are given in Table I.

Table I

Error signals (in percentage of full scale) for ± 9g applied in transverse direction

No. of transducers	145	177	209
Compression or tension in springs	1.4	1.8	1.3
Edgewise shear in springs	1.5	1.5	1.4

These figures (giving an average transverse sensitivity of approximately 0.15% per one transverse g applied) will produce no appreciable error in the majority of applications. Very similar values have been measured for a transducer of ± 3g range, if ± 3g acceleration is applied in a transverse direction.

3.4 Temperature sensitivity

A change in the temperature of a transducer may result in two effects:

(a) Variation of zero setting under the no-load condition. (zero-lift)

(b) Variation of slope of the calibration curve (variation in sensitivity)

Both effects may be investigated under steady thermal conditions when there is temperature equilibrium in all parts of the transducer, or under conditions of a temperature impact when there is a temperature gradient in the transducer. The behaviour of this transducer in the latter condition has not been investigated thoroughly, as it is assumed that in the majority of cases the transducer will be used under conditions of temperature equilibrium. As long as equilibrium is not reached, a temperature gradient will exist inside the transducer, the distribution and magnitude of which will depend on time, heat capacity of the surroundings (especially of the structure the transducer is fixed to), and on the magnitude of the temperature impact. Results, therefore, will be of a very limited value.

(a) Zero shift

Table II gives the zero shift error in percentage of full scale per °C at temperature equilibrium, calculated from an experimental temperature rise of about 30°C.

(b) Variation in sensitivity

Table II also gives the variation in sensitivity in percentage of full scale per °C at equilibrium temperature calculated from an experimental temperature rise of about 30°C.

Table II

Temperature errors under equilibrium conditions for ± 9g transducer

No. of transducers	145	177	209
Zero shift error in % full scale per °C	+0.04	+0.05	+0.03
Variation in sensitivity; Error in % full scale per °C	-0.085	-0.21	-0.085

4 Electrical characteristics

The transducer when in use forms two adjacent arms of an A.C. bridge circuit energised by an alternating voltage of 10 volts R.M.S. at 2,000 c/sec. The other two arms of the bridge are two resistances R (1,000 ohms each in the amplifiers referred to). The bridge out-of-balance voltage is applied through a transformer of primary resistance R_T (2,000 ohms in the same amplifier) to a band-pass amplifier, phase sensitive detector, and suitable galvanometer recorder. At present the transducer is mainly used with amplifier Type IT.1-5-51 and power unit type IT.1-6-51, but any other equipment may be used if the electrical characteristics of the transducer are suitable.

4.1 Variation of Inductance and storage factor

The vector diagram of the impedance of one typical transducer coil at various frequencies is shown in Fig 7a. The series inductance L and series loss resistance R_S with a three-cored cable of 2' 6" length attached to the transducer have been measured under mechanical no-load conditions. In the course of development of the transducer the magnetic material of the core and armature was changed from Radio metal, in

laminations of 0.004 inch thickness, to Ferroxcube III; due to the relatively large airgap no appreciable change in inductance resulted. In Fig 7a impedance values for Radio metal cores and armature are plotted for comparison.

Also, at a carrier frequency of 2,000 c/sec the airgap of the magnetic circuit of the coil was varied by ± 0.1 mm and ± 0.2 mm. The corresponding impedances are plotted in Fig 7b. It is seen that they lie on a straight line almost parallel to the impedance characteristic of Fig 7a, but the non-linear behaviour of the impedance variations for these large deflections is obvious.

The storage factor $Q = \omega L/R_s$ of the coil is represented by the tangent of the angle φ between the real axis and a vector to any point on the curve.

Fig 8 gives the variation of inductance L and storage factor Q at 2,000 c/sec of a transducer coil for a variable airgap ℓ between core and armature. For a full scale working deflection of the armature of about ± 0.07 mm or ± 0.003 inch, the average percentage change in inductance is about ± 15% of an initial inductance of 70 mH at an initial airgap of 0.24 mm or almost 0.01 inch. The storage factor Q varies between about 4.5 and 6.

4.2 Current sensitivity

It has been shown[1] that the output current I_o of an A.C. bridge circuit containing a variable inductance push-pull transducer after phase sensitive rectification which rejects the quadrature component, is

$$I_o = k \cdot V_i \frac{R_T W_2 \omega}{W_1^2 + W_2^2} \left(\frac{W_1}{\omega W_2} \Delta R_s + \Delta L \right) \qquad (1)$$

where

V_i = bridge energising voltage in volts

R_T = load resistance of bridge (2,000 ohms)

W_1 = $R_s (R_s + R + 2 R_T) - \omega^2 L^2$

W_2 = $\omega L (2 R_s + R + 2 R_T)$

R = resistance of ratio arm (1,000 ohms)

L = series inductance of coil in Henrys

R_s = series loss resistance of coil in ohms

ΔL = variation of inductance due to acceleration

ΔR_s = variation of loss resistance due to acceleration

ω = $2\pi \times$ carrier frequency (2π 2,000 sec^{-1})

k = constant, depending on amplification, with dimensions of a conductance.

The parameters of the transducer, dependent on the applied acceleration, are ΔR_s and ΔL. For constant amplification and input voltage the overall current sensitivity of the bridge to a change in

inductance is governed by $(R_T W_2 \omega)/(W_1^2 + W_2^2)$ and the relative contribution of a change in loss resistance by $W_1/(W_2 \omega)$. These two factors are plotted in Fig 9a and 9b, relative to their values at 2,000 c/sec. The first factor shows a flat maximum at about 2,300 c/sec, and at this frequency the second factor is zero, i.e. the loss resistance (or any other variable resistance in the transducer circuit) does not contribute to the sensitivity. It can be shown, that these two conditions exist when $W_1 = 0$.

The characteristics of the transducer and bridge circuit are thus such that the combination is operated very near the condition of maximum current sensitivity, and the contribution of loss resistance is very nearly zero. This later property is desirable as ΔR_S is likely to have a relatively high resistive noise level.

The curve already considered in Fig 9a and 9b are derived for a constant input voltage to the bridge. As the impedance of the transducer coil increases with frequency the bridge energising voltage may be increased proportionally, maintaining a fixed value of current in the transducer coils, provided that the higher current in the ratio arms of the bridge can be tolerated. In this case the output current for change in inductance is proportional to $(R_T \; W_2 \; \omega^2)/(W_1^2 + W_2^2)$. This factor is plotted against frequency in Fig 9a as a dotted curve. It shows a continuous increase with frequency as expected.

4.3 Power sensitivity (matching)

From equation (1) the power output from the demodulator is

$$P_o = V_i^2 \frac{R_T W_2^2 \omega^2}{(W_1^2 + W_2^2)^2} \left(\frac{W_1}{\omega W_2} \Delta R_S + \Delta L\right)^2.$$

The power output due to change in inductance only, i.e. when W_1 is made zero, is

$$P_o = V_i^2 \cdot \frac{R_T}{(2 R_S + R + 2 R_T)^2} \cdot \left(\frac{\Delta L}{L}\right)^2 .$$

When V_i and $\Delta L/L$ are considered fixed, the maximum power output occurs when

$$R_T = R_S + R/2 .$$

Combining this result with the results of the preceding section, we have two conditions for the optimum design of the transducer and its associated bridge circuit.

(a) for freedom from resistive noise

$$\omega^2 L^2 = R_S (R_S + R + 2 R_T)$$

(b) for maximum useful power output

$$R_S = R_T - R/2$$

The usual approach is to design the transducer on the basis of other necessary conditions, as size etc. and then select the bridge parameters to satisfy the present conditions. From these the bridge parameters R and R_T are given by

$$R = \tfrac{1}{2} \omega LQ (1 - 3/Q^2)$$

$$R_T = \tfrac{1}{4} \omega LQ (1 + 1/Q^2)$$

when $$Q = \omega L/R_S$$

The ratio R/R_T depends only on Q and is given by

$$R/R_T = \frac{2 (Q^2 - 3)}{Q^2 + 1} .$$

In Fig 10 the values of $R_T/\omega L$ and in Fig 11 those of R/R_T are plotted against Q. For large values of Q we have $R/R_T \simeq 2$. for values of $Q < \sqrt{3}$ no value of R/R_T exists.

4.4 <u>Effect of mutual coupling between transducer coils</u>

This general problem has been considered elsewhere[1]. Applying these results to the present case, it may be shown that the mutual coupling between the two transducer coils is small and has only about a 2% effect on the sensitivity.

4.5 <u>Effect of cable capacitance</u>

It can be shown[1] that the fractional change of inductance with a capacitance C in parallel with the transducer coil is

$$\frac{\Delta L'}{L'} = \frac{1}{1 - \omega^2 LC} \cdot \frac{\Delta L}{L}$$

i.e. below the electrical resonance conditions, which is usually the case in practice, the sensitivity of an inductance transducer increases with the capacitance connected in parallel with its coil.

For a typical transducer coil with a cable 100 yards long connected to it we have

$$L = 64 \text{ mH at } 2{,}000 \text{ c/sec}$$

$$C = 0.005 \ \mu F$$

$$\omega = 2\pi\, 2{,}000 \text{ sec}^{-1}$$

and

$$\frac{\Delta L'}{L'} = 1.05 \frac{\Delta L}{L}$$

i.e. an increase in sensitivity of 5%. This has been verified experimentally in the present case.

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No.	Author	Title, etc.
1	H.K.P. Neubert	Design and performance of inductance pick-ups and their associated circuits. R.A.E. Report No. Instrumentation 7.

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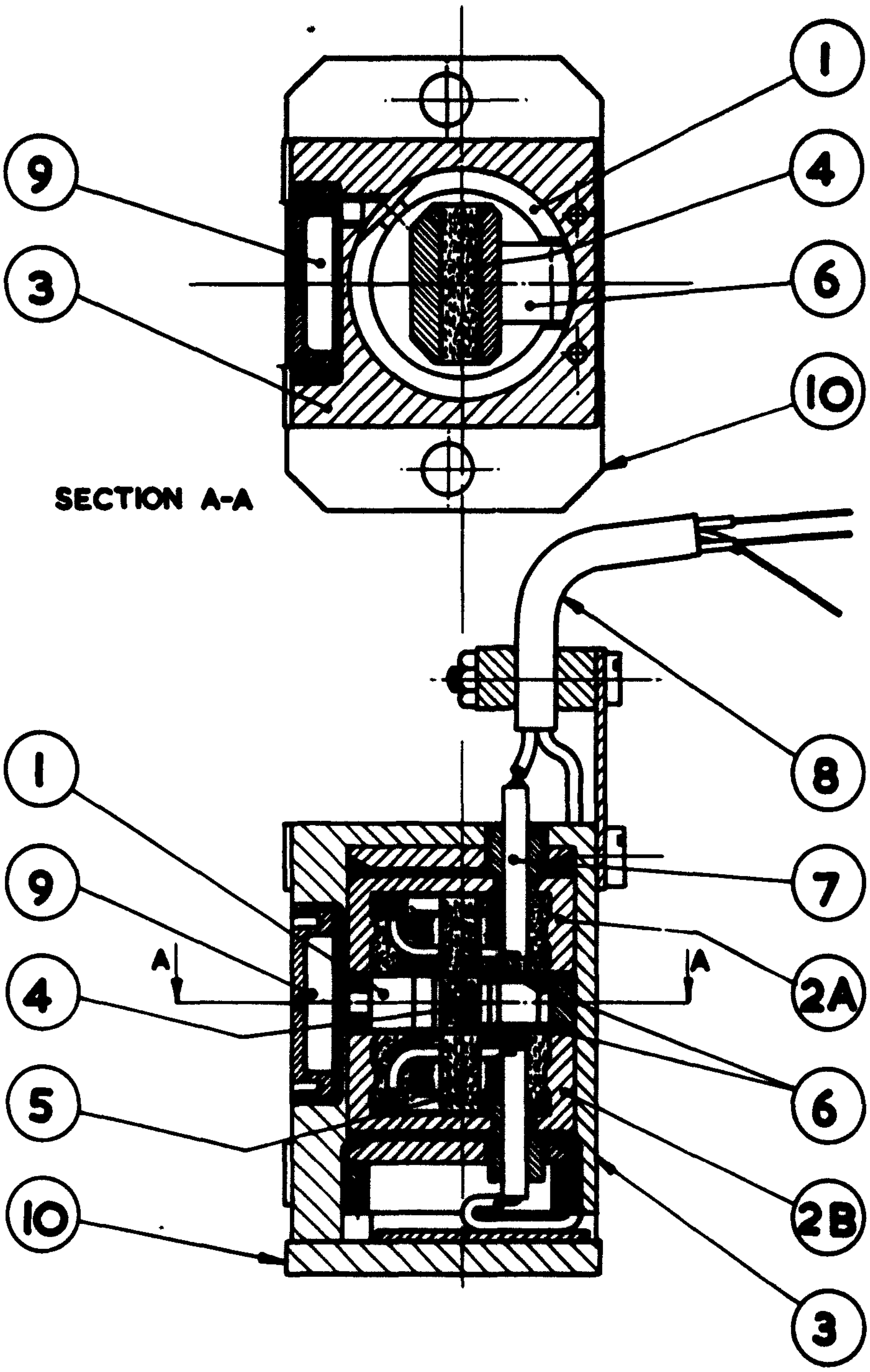
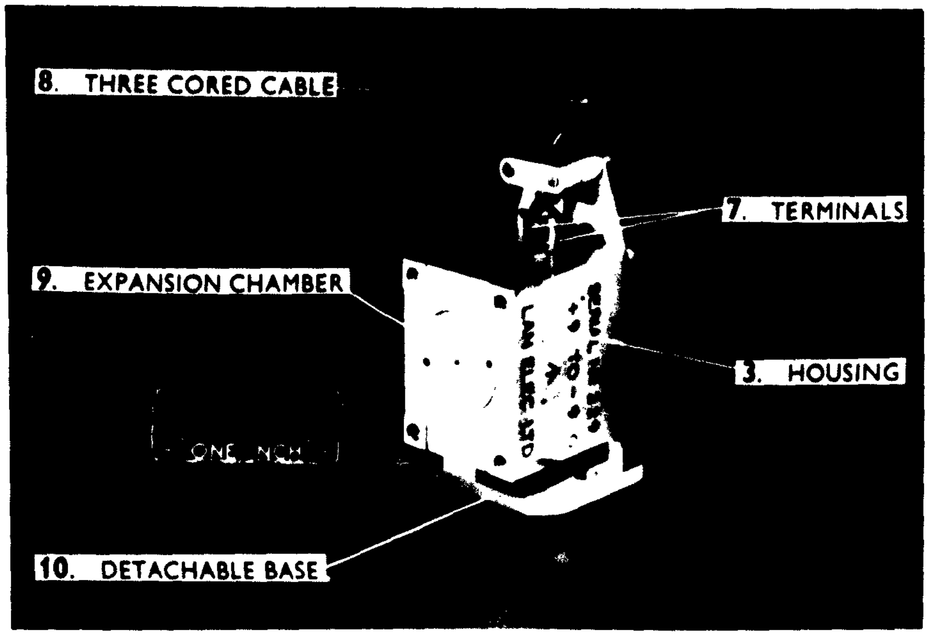


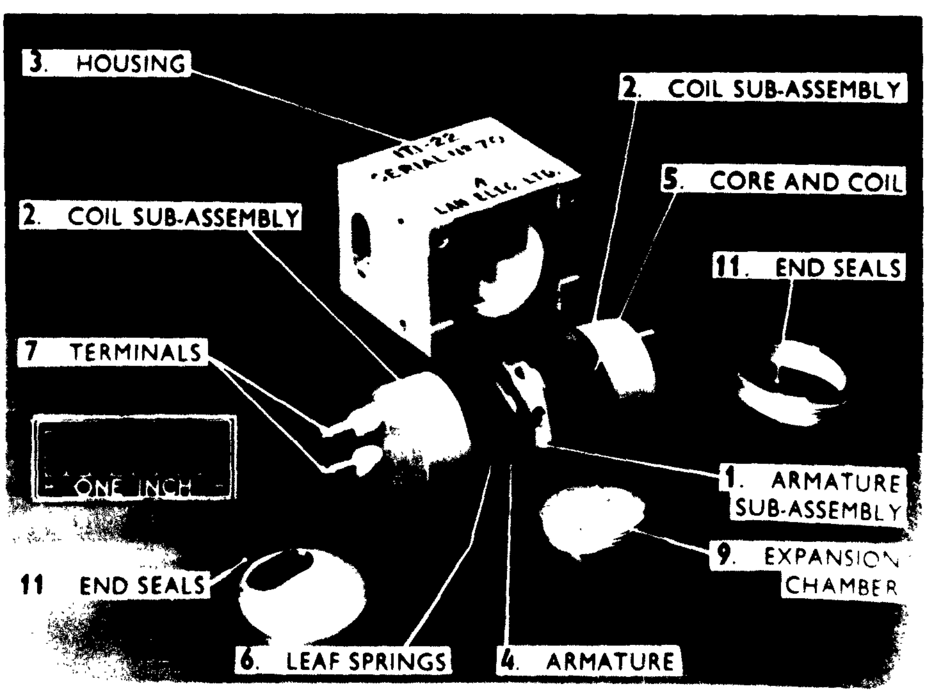
① ARMATURE SUB/ASS'Y
② COIL SUB/ASS'Y'S
③ HOUSING
④ ARMATURE
⑤ CORE & COIL
⑥ LEAF SPRINGS
⑦ TERMINALS
⑧ THREE CORE CABLE
⑨ EXPANSION CHAMBER
⑩ DETACHABLE BASE

FIG.1 CONSTRUCTION OF ACCELERATION TRANSDUCER TYPE IT. 1-22F-31

FIG.2



a COMPLETE TRANSDUCER



b. EXPLODED TRANSDUCER

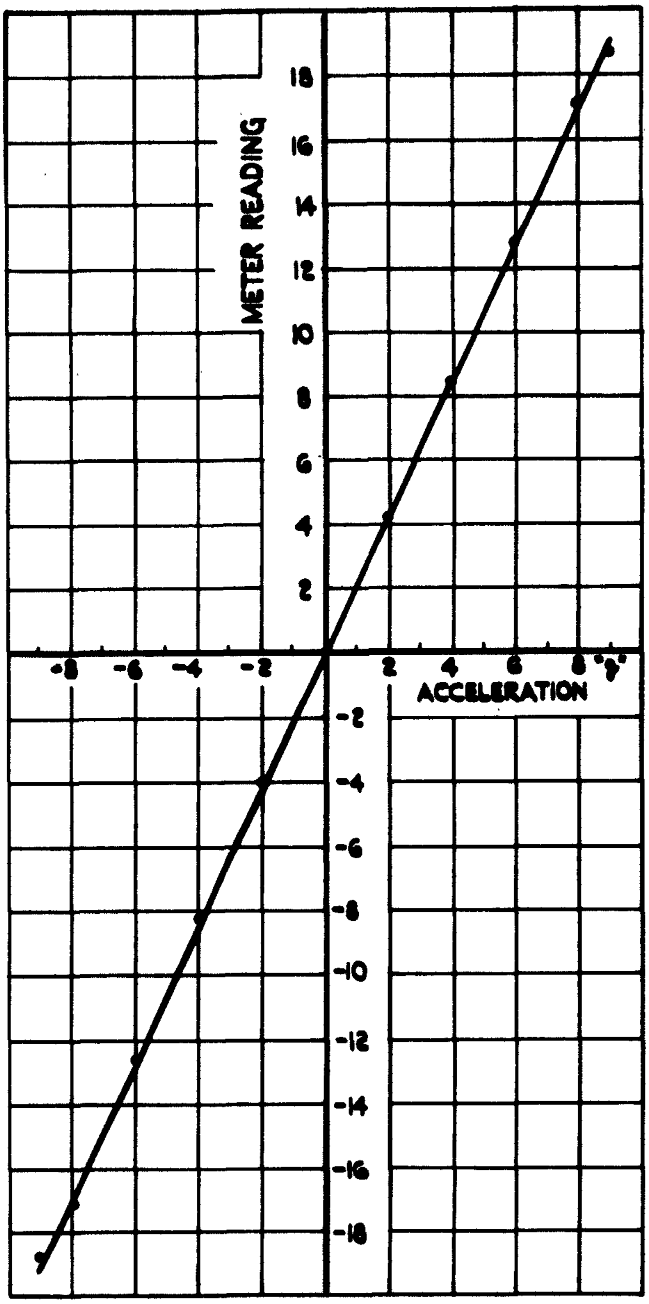


FIG.3 TYPICAL CALIBRATION CURVE OF TRANSDUCER.

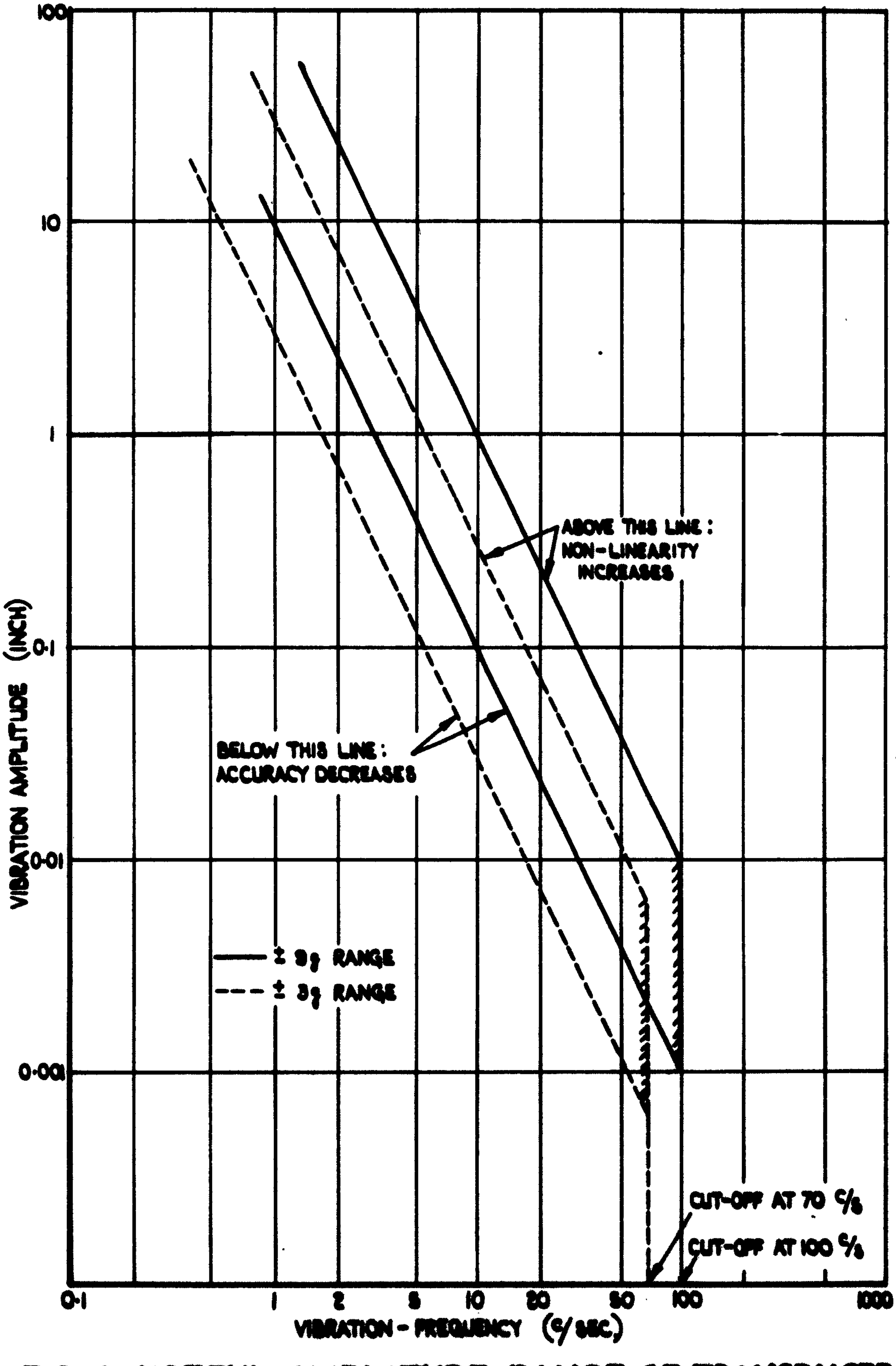


FIG. 4 USEFUL AMPLITUDE RANGE OF TRANSDUCER FOR VARIOUS FREQUENCIES.

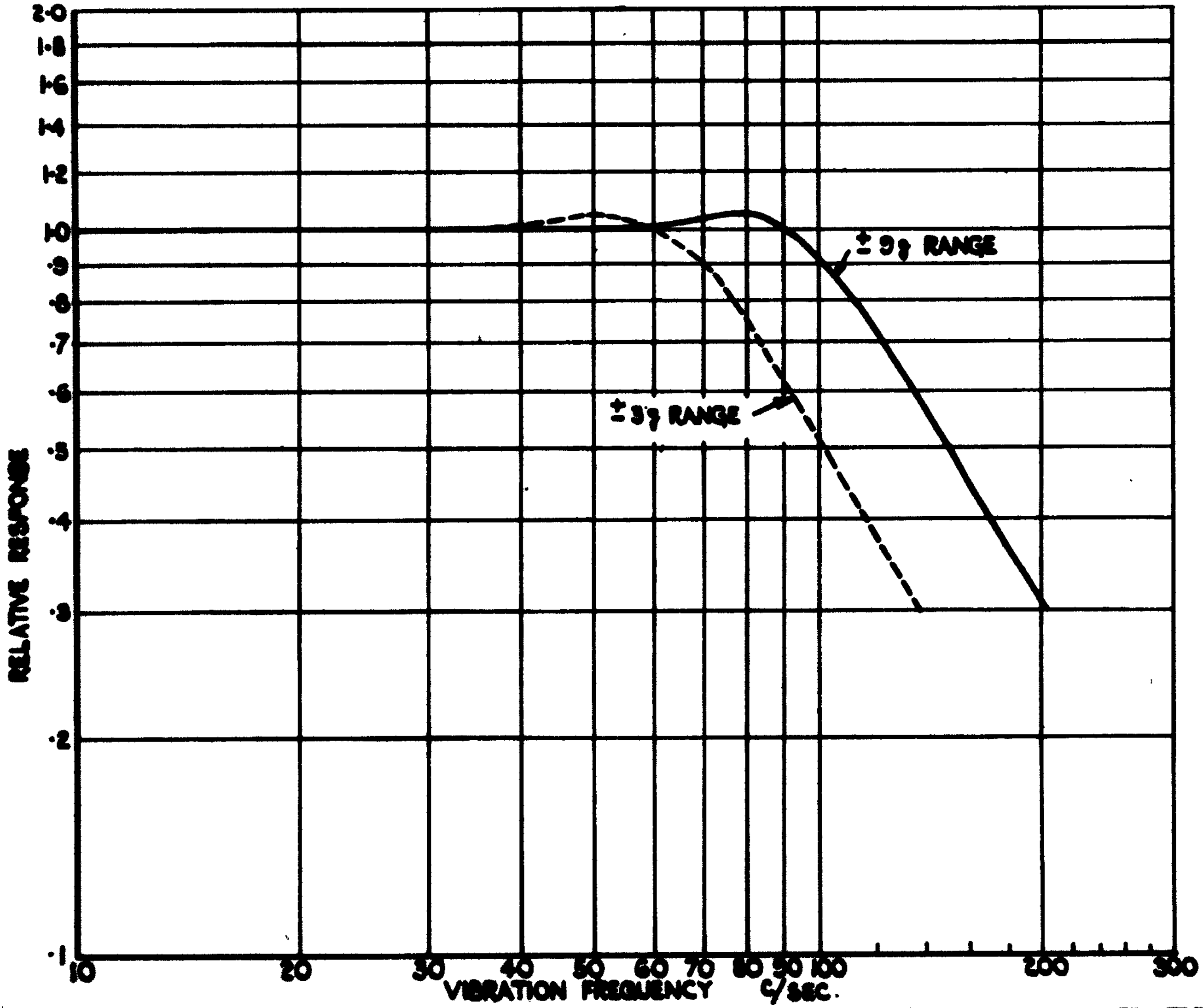


FIG. 5 FREQUENCY RESPONSE OF TRANSDUCER TO SINUSOIDAL ACCELERATION (+25°C)

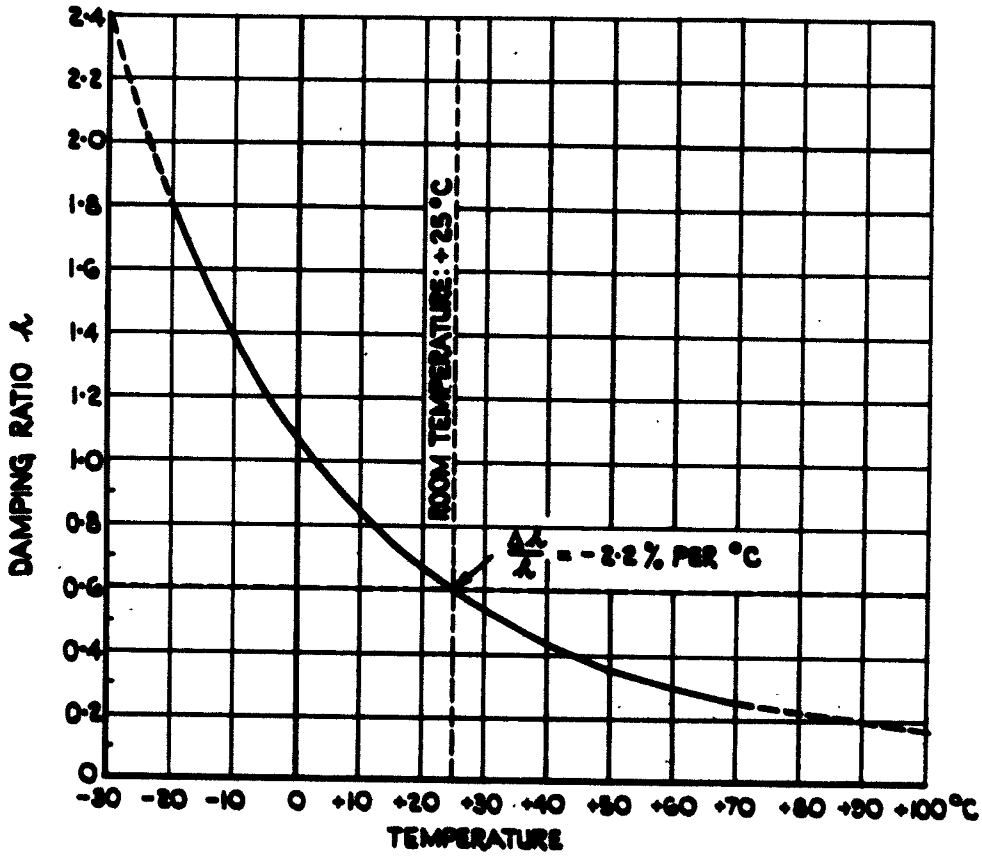
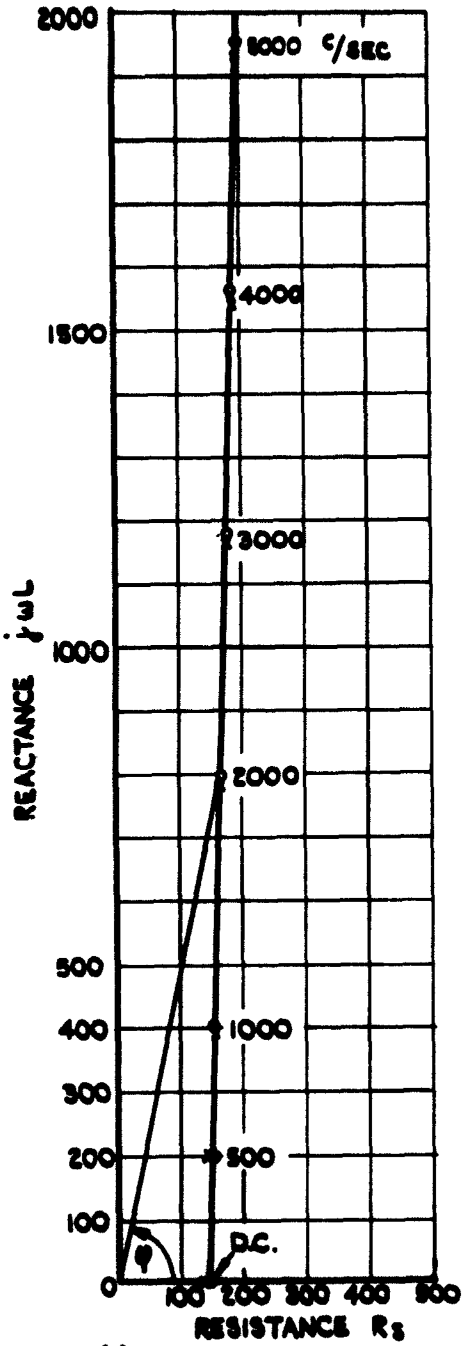
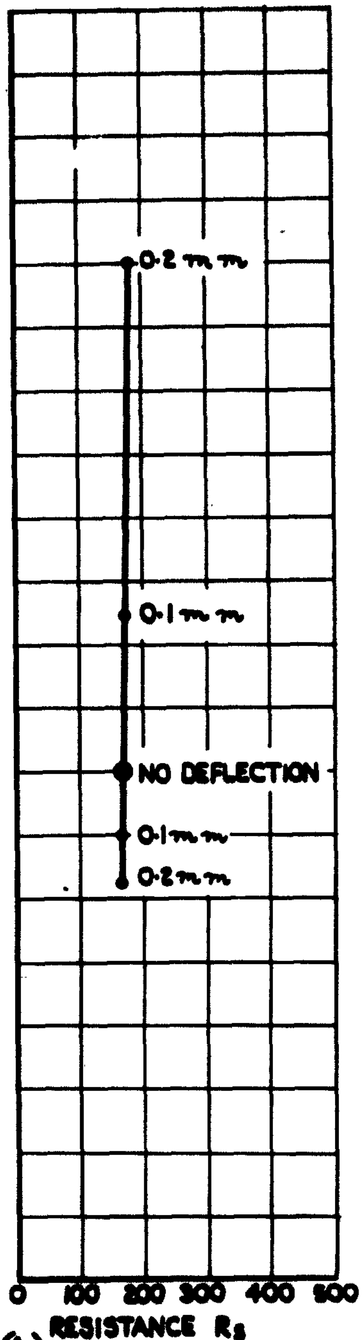


FIG.6 VARIATION OF DAMPING RATIO OF TRANSDUCER WITH TEMPERATURE



(a)

IMPEDANCE OF TRANSDUCER COIL AT VARIOUS FREQUENCIES. ARMATURE AT ZERO POSITION



(b)

VARIATION OF IMPEDANCE OF TRANSDUCER COIL AT 2000 c/sec CARRIER FREQUENCY AT ZERO AND DEFLECTED POSITIONS OF ARMATURE.

FIG. 7(a & b) IMPEDANCE OF TRANSDUCER COIL

(a) AT VARIOUS FREQUENCIES

(b) AT VARIOUS AIR-GAPS

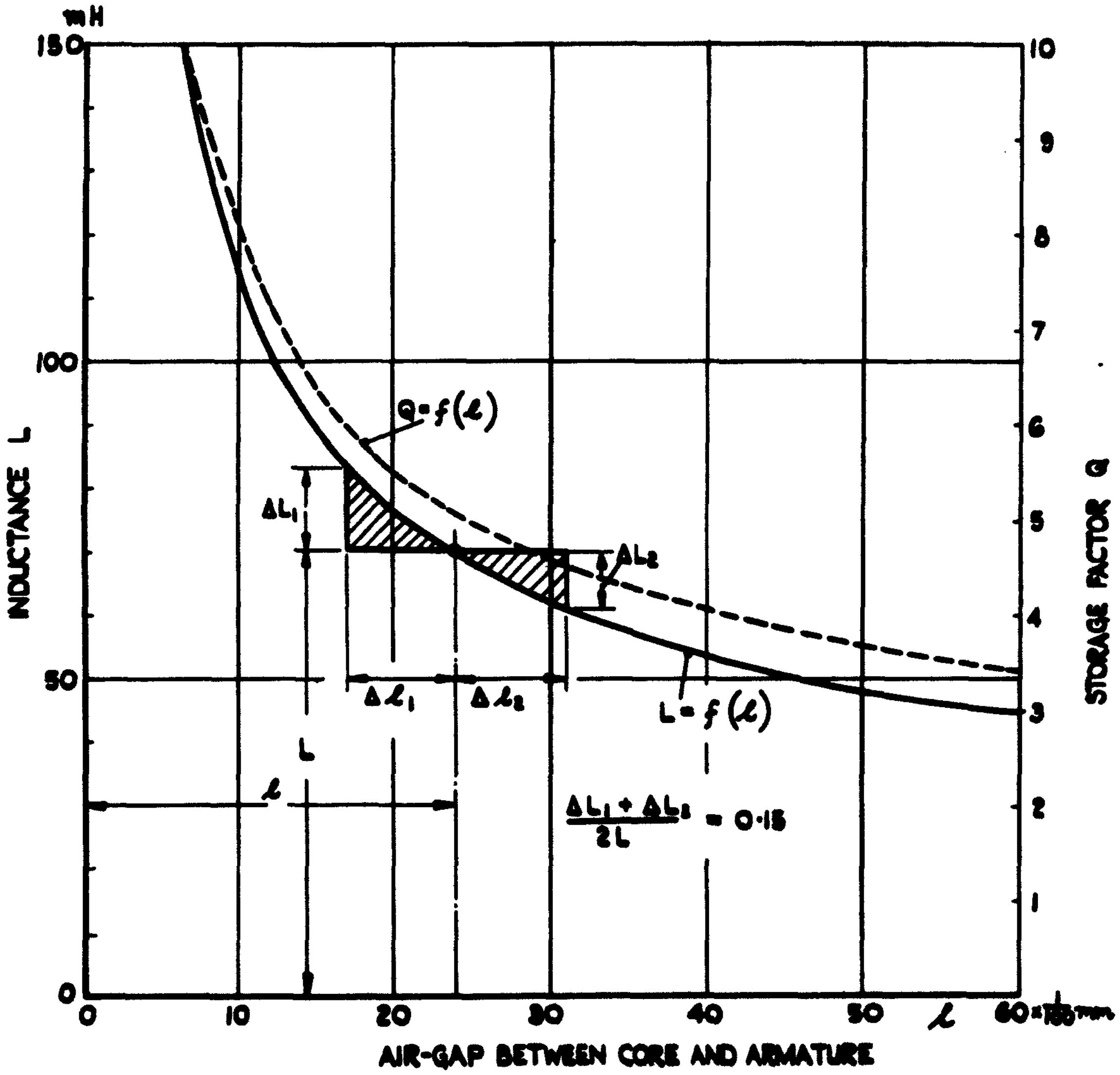
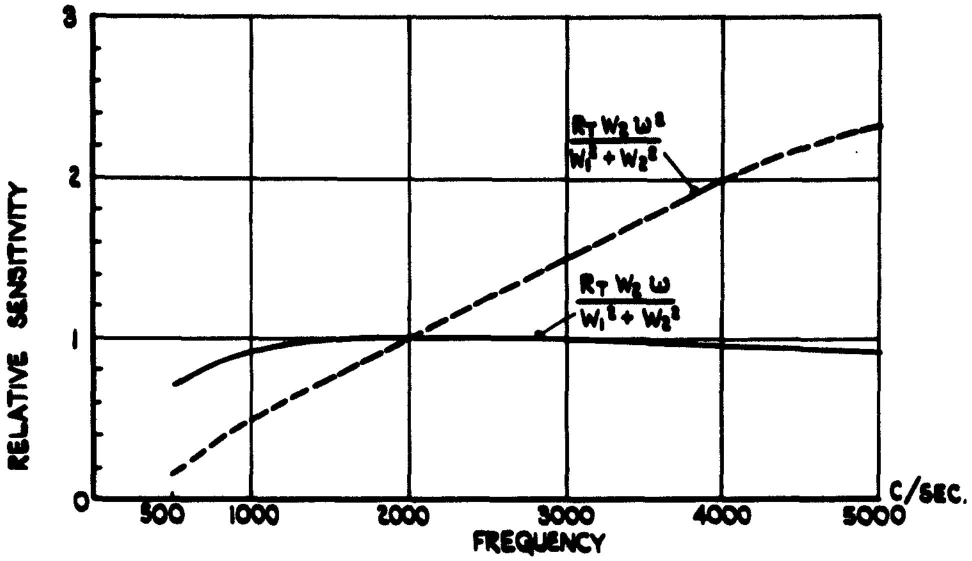
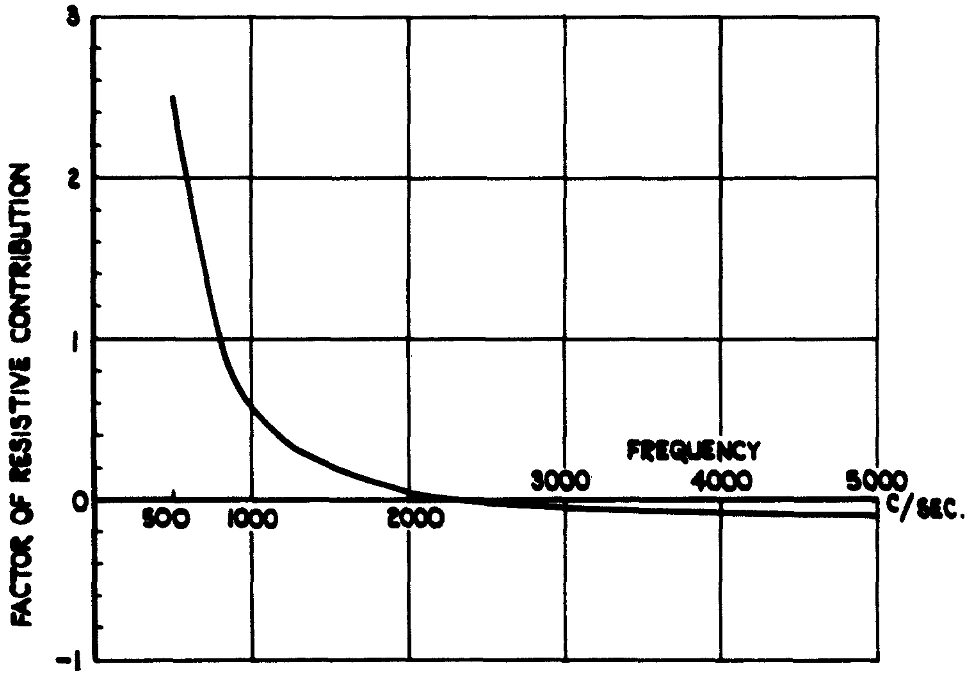


FIG. 8 VARIATION OF INDUCTANCE L AND STORAGE FACTOR Q OF TRANSDUCER COIL WITH AIR-GAP ℓ



(a)



(b)

FIG. 9 (a & b) CURRENT SENSITIVITY OF TRANSDUCER.

(a) RELATIVE CURRENT SENSITIVITY AT VARIOUS CARRIER FREQUENCIES.

(b) FACTOR OF RESISTIVE CONTRIBUTION TO SENSITIVITY AT VARIOUS CARRIER FREQUENCIES.

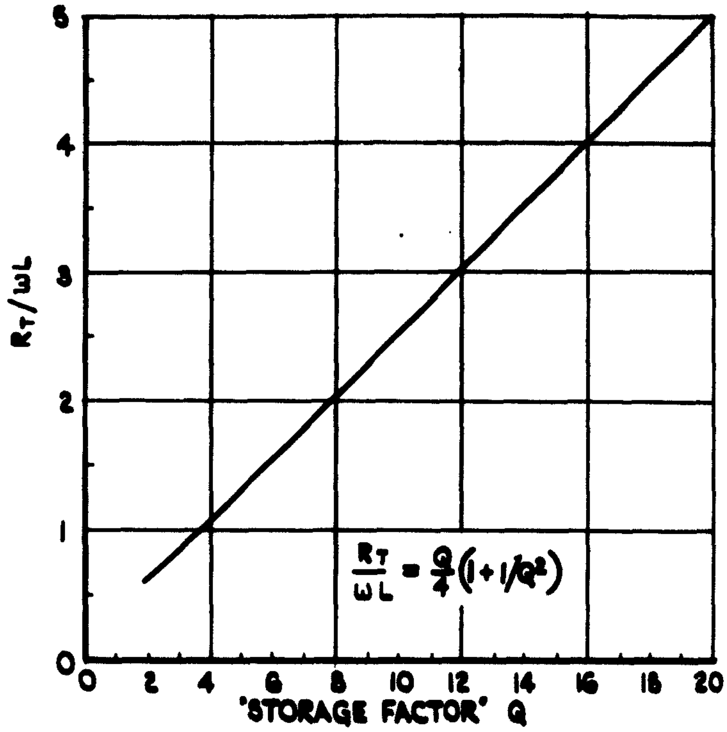


FIG.10 RATIO OF LOAD RESISTANCE $\underline{R_T}$ TO REACTANCE $\underline{\omega L}$ AS A FUNCTION OF STORAGE FACTOR $\underline{Q}$ FOR OPTIMUM BRIDGE DESIGN.

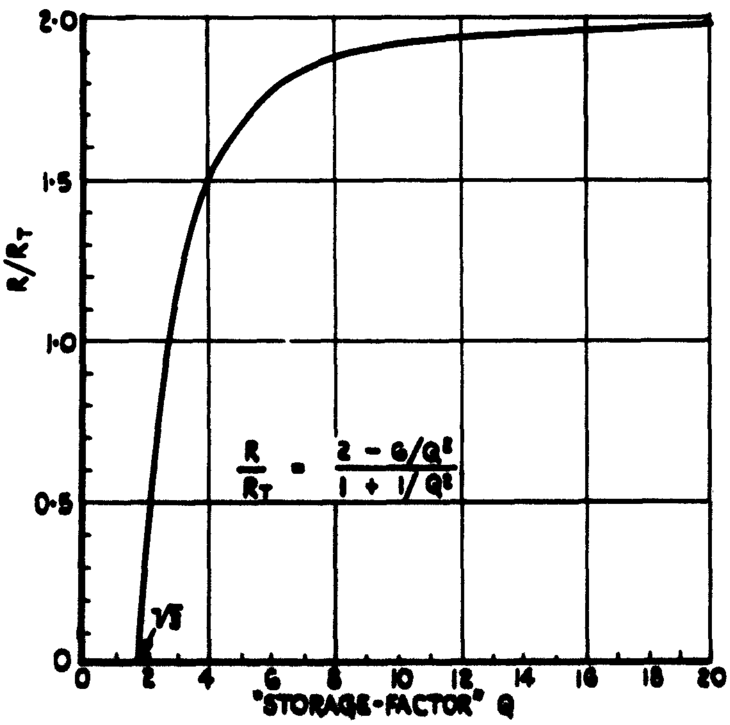


FIG.11 RESISTANCE RATIO $\underline{R/R_T}$ AS A FUNCTION OF STORAGE FACTOR $\underline{Q}$ FOR OPTIMUM BRIDGE DESIGN.

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Design parameters for the bridge resistance values are derived and plotted for two independent conditions:- (a) freedom from resistive noise and (b) maximum useful power output from the bridge. The effect of cable capacitance and of mutual coupling between the transducer coils are also discussed.

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